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Abstract

The rapid chloride permeability test (RCPT) (AASHTO T 277, ASTM C 1202) is increasingly being used as an acceptance test for concrete constructions in the transportation industry. As more and more projects are subject to such testing, the capabilities of agency laboratories to conduct the test in a timely fashion are strained.

A literature review regarding the RCPT revealed that the electrical conductivity of concrete is a more valid indicator of its quality than the RCPT result and that the conductivity can be determined from a measurement of the current taken 1 to 10 minutes after the voltage is applied using the standard equipment setup. A series of tests was conducted that estimated the within-laboratory precision of the conductivity measurement and the standard 6-hour RCPT. Comparison of the estimates indicated that the conductivity measurement is more precise than the RCPT. Conductivity values were calculated from a large block of RCPT data, and regression analysis was used to examine the relationship between the two measures. Confidence limits for the regression can be used to determine the range of RCPT values expected from a given conductivity value to facilitate shifting from an RCPT-based criterion to one based on concrete conductivity.

The benefits of implementing these recommendations provided would be as follows:

- Routine acceptance testing of concrete for chloride permeability would be streamlined without increased cost.

- Such acceptance testing could be conducted within 1 to 10 minutes, as compared to 6 hours for the existing test procedure, thus greatly reducing the backlog associated with such testing. This would permit the timely reporting of test results to project personnel and allow more effective management.

- The new test recommended has improved repeatability when compared with the current test.

FINAL REPORT

SUPPLANTING THE RAPID CHLORIDE PERMEABILITY TEST WITH A QUICK MEASUREMENT OF CONCRETE CONDUCTIVITY

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Virginia Department of Transportation and
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DISCLAIMER

ABSTRACT

The rapid chloride permeability test (RCPT) (AASHTO T 277, ASTM C 1202) is increasingly being used as an acceptance test for concrete constructions in the transportation industry. As more and more projects are subject to such testing, the capabilities of agency laboratories to conduct the test in a timely fashion are strained.

A literature review regarding the RCPT revealed that the electrical conductivity of concrete is a more valid indicator of its quality than the RCPT result and that the conductivity can be determined from a measurement of the current taken 1 to 10 minutes after the voltage is applied using the standard equipment setup. A series of tests was conducted that estimated the within-laboratory precision of the conductivity measurement and the standard 6-hour RCPT. Comparison of the estimates indicated that the conductivity measurement is more precise than the RCPT. Conductivity values were calculated from a large block of RCPT data, and regression analysis was used to examine the relationship between the two measures. Confidence limits for the regression can be used to determine the range of RCPT values expected from a given conductivity value to facilitate shifting from an RCPT-based criterion to one based on concrete conductivity.

The benefits of using the conductivity measurement for acceptance testing would be as follows:

- Routine acceptance testing of concrete for chloride permeability would be streamlined without increased cost.

- Such acceptance testing could be conducted within 1 to 10 minutes, as compared to 6 hours for the existing test procedure, thus greatly reducing the backlog associated with such testing. This would permit the timely reporting of test results to project personnel and allow more effective management.

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INTRODUCTION

The resistance of concrete to penetration by chlorides is an important factor in protecting reinforced concrete structures from premature deterioration. Because of the time needed to measure the resistance directly, a relatively rapid, indirect method was developed (Whiting, 1981). The test method, commonly referred to as the rapid chloride permeability test (RCPT), has been standardized (AASHTO T 277 [American Association of State Highway & Transportation Officials, 2003] and ASTM C 1202 [ASTM International, 2003]).

The RCPT measures the electrical charge passed (in Coulombs) through a disk of saturated concrete under a 60 V DC potential applied between electrodes in solution-filled cells on opposite sides of the disk during a 6-hour test period. NaCl mass) and NaOH (1M) solutions fill the cells on opposite sides of the test specimen. The charge passed is not a direct measure of the permeability of the concrete with respect to chloride ions, although NaCl is used in an effort to reinforce this concept; however, it does provide a fairly good indication of the resistance of concrete to the penetration of chlorides by diffusion (McGrath and Hooton, 1999). The RCPT has been adopted as a specification tool by many agencies concerned with preventing chloride-induced corrosion damage to reinforced concrete.

The Virginia Department of Transportation (VDOT) uses AASHTO T 277 with minor modifications (Virginia Test Method 112) as an acceptance test for particular projects. VDOT established maximum values for three classes of concrete, as shown in Table 1.

VDOT Materials Division staff estimated that approximately 30% of the concrete being used in VDOT construction projects is currently subject to the permeability specification, and its application is expected to increase. Permeability requirements are a major part of developing an end-result specification, and the adoption of the permeability specification will result in most VDOT concrete being subject to such requirements. In current practice, concrete

Table 1. VDOT Criteria for Low-permeability Concretes Using AASHTO T 277 (VTM 112)

Concrete Class	Maximum Value at 28 Days (Coulombs)
Prestressed and other special designs (e.g., low-permeability overlays)	1500
A4 General, A4 Posts & rails	2500
A3 General, A3 Paving	3500

cylinders are fabricated by VDOT district materials personnel at the project site and then transported to the central laboratory of VDOT's Materials Division, where test specimens are prepared and the testing is performed. Because of the distances involved, transport is usually accomplished in two stages: from the project to the district laboratory, where cylinders are collected and stored until a trip to the central laboratory is warranted, and then to the central laboratory. This process is efficient. At the central laboratory, the cylinders undergo accelerated curing at 100^{o} F for 21 days. After curing, 2-inch test specimens are cut from the cylinders. Specimen preparation involves coating the sides with epoxy to prevent peripheral drying of the specimen during the test and then allowing several hours for the epoxy to cure. Immediately prior to testing, specimens are vacuum saturated over a 4-hour period followed by 16 to 20 hours of soaking in water. The 6-hour test is then conducted.

PROBLEM STATEMENT

Although transporting the cylinders does not cause delays in the testing process, the central laboratory routinely receives more cylinders in a day than can be tested. This creates a significant backlog, resulting in delays in report results.

PURPOSE AND SCOPE

This study entailed an examination of the RCPT by means of a literature review, laboratory testing, and data analysis with the purpose of streamlining VDOT's acceptance testing process.

METHODS

The methods comprised three tasks.

1. *A review of the literature regarding the scientific basis of the RCPT was conducted.* Pertinent articles identified in a survey of recent journals and publications were reviewed.

2. *RCPTs (ASTM C 1202) were conducted on a suite of four concrete mixtures alongside measurements of concrete conductivity made in accordance with a method under development by ASTM* (Proposed New Test Method for Indication of Concrete's Ionic Conductivity). As a part of its standards development activities, ASTM Subcommittee C09.66 is conducting an inter-laboratory testing program to study the precision of methods related to concrete permeability in which the Virginia Transportation Research Council (VTRC) is a participant. The program is examining two electrical tests, RCPT and ionic conductivity; two chloride penetration tests, bulk diffusion and ponding; and a sorption test. Test specimens were fabricated from four concrete mixtures by Degussa Admixtures, Inc., and distributed to the participating laboratories. Three of the mixtures were portland cement concretes with w/cms of 0.58, 0.48, and 0.38. The fourth

mixture had a w/cm of 0.38 and contained 6% silica fume by mass of cement. This report discusses only the results from VTRC for the electrical tests.

The conductivity test and RCPT were conducted using the standard RCPT setup except that the sides of the specimens were taped rather than coated with epoxy and NaOH solution was used as the electrolyte in the cells on both sides of the specimen. NaOH was used rather than NaCl because the corrosive nature of NaCl toward the electrode creates maintenance problems. Current readings were recorded at 1, 5, and 10 min after the voltage was applied across the specimen, and conductivity values were computed using Equation 2. The test was continued and data were collected to compute the RCPT 6-hour total charge passed.

$$\sigma = l / (R\ A) \qquad \text{[Eq. 2]}$$

where

σ = conductivity (Siemens/m)
l = length in mm
R = resistance (Ohms)
A = area (m^2).

3. *A large block of existing rapid chloride permeability data consisting of time and current measurements collected by VTRC was examined to calculate the conductivity values for these concretes.* These values were then regressed against the 6-hour RCPT results by the least-squares fit method to establish the correlation between the two variables.

RESULTS AND DISCUSSION

Literature Review

The RCPT is an electrical test operating under Ohm's law (Equation 1) in which the test result is a direct function of the resistance of the test specimen (Julio-Betancourt and Hooton, 2004).

$$V = IR \qquad \text{[Eq. 1]}$$

where

V = potential, in Volts
I = current, in amperes
R = resistance, in Ohms.

In principle, the use of electrical properties to measure the ionic transport properties of concrete is well grounded (McCarter et al., 2000) and is affected by two aspects of the concrete: (1) the connectivity of the capillary pore system, and (2) the electrolytic capacity (ionic concentration) of the pore solution. Of primary interest with respect to assessing the durability of concrete is the capillary pore system. RCPT results correlate fairly well with chloride penetration by diffusion (McGrath and Hooton, 1999) in which the pore system has the primary influence on results, and thus the same conclusion can be drawn for the electrical test. Two notable exceptions where the ionic concentration of the pore solution greatly affects RCPT results occur with silica fume (very low) (Shi et al., 1998) and calcium nitrite (very high) (ASTM C 1202). To remove the influence of ionic concentration in this type of test, Streicher and Alexander (1995) suggested saturating test specimens with 5M NaCl solution.

In practice, the current driven by the 60-V potential is monitored and integrated over time to measure the total charge passed (or conductance) of the concrete over the 6-hour test period in Coulombs (ampere-seconds). As current passes through the specimen (a resistor), resistance (ohmic) heating of the specimen takes place and in turn increases the conductivity of the specimen through the Joule effect (Feldman et al., 1994; Snyder et al., 2000; and Julio-Betancourt and Hooton, 2004). Feldman et al. (1994) also indicate that changes in the pore structure and pore solution chemistry may occur in response to the passing of current during the test, further affecting the results, and that almost any electrolytic solution can be used in the cells on both sides of the specimen.

These authors all agree that conductivity (conductance per unit area) (or its inverse, resistivity) is directly related to chloride diffusivity and is easily determined for the concrete within minutes using the RCPT setup. Conducting the test for 6 hours and measuring the charge passed provide a confounded result because of changes induced in the specimen in response to the test conditions. Resistivity of concrete is also an important factor affecting the rate of corrosion once it is initiated (Carino, 2004), with high resistivity (low conductivity) impeding the rate of corrosion.

RCPT and Conductivity Test

The RCPT AND conductivity test results are shown in Table 2.

Examination of the data presented in Table 2 shows essentially no difference between the conductivity values computed using the 1-min, 5-min, and 10-min currents. Within-batch averages and standard deviations (SD) established that the SD tends to increase with increasing test values, indicating that the coefficient of variation (COV) should be used as the measure of precision. The COV results for the four batches were pooled to provide an estimate of repeatability (within-laboratory or single-operator precision). The repeatability of the RCPT estimated from these tests, 8.28%, compared favorably with the estimate reported in ASTM C 1202: 12.3%. The estimated repeatability values for the 1-min, 5-min, and 10-min conductivity tests were 5.04%, 4.95%, and 4.63%, respectively.

Figure 1 is a plot of the 1-min conductivity value against the RCPT value for each specimen. The plotted data clearly suggest a linear relationship, and the regression line equation and correlation coefficient are presented.

Table 2. Conductivity (1-min and 5-min) and RCPT Results for Four Concrete Mixtures

Specimen	Cementitious Material	W/CM	1-min σ (S/m)	5-min σ (S/m)	10-min σ (S/m)	6-hour RCPT (Coulombs)
1a	PC	0.58	0.0160	0.0158	0.0159	3222
1b	PC	0.58	0.0170	0.0171	0.0175	4130
1c	PC	0.58	0.0149	0.0152	0.0155	3404
Avg	PC	0.58	0.016	0.016	0.016	3586
SD			0.00102	0.00101	0.00104	480
COV			6.40%	6.32%	6.37%	13.38%
2a	PC	0.48	0.0132	0.0131	0.0131	2635
2b	PC	0.48	0.0126	0.0125	0.0127	2689
2c	PC	0.48	0.0131	0.0132	0.0134	2906
Avg	PC	0.48	0.013	0.013	0.013	2743
SD			0.00034	0.00035	0.00037	144
COV			2.60%	2.72%	2.84%	5.24%
3a	PC	0.38	0.0104	0.0103	0.0104	1971
3b	PC	0.38	0.0098	0.0098	0.0098	1998
3c	PC	0.38	0.0087	0.0087	0.0088	1698
Avg	PC	0.38	0.010	0.010	0.010	1889
SD			0.00083	0.00082	0.00079	166
COV			8.57%	8.51%	8.16%	8.79%
4a	PC + 6% SF	0.38	0.0027	0.0026	0.0026	474
4b	PC + 6% SF	0.38	0.0028	0.0027	0.0027	517
4c	PC + 6% SF	0.38	0.0027	0.0027	0.0026	465
Avg	PC + 6% SF	0.38	0.003	0.003	0.003	485
SD			0.00007	0.00006	0.00006	28
COV			2.58%	2.25%	2.36%	5.72%
Pooled COV, repeatability			5.04%	4.95%	4.63%	8.28%

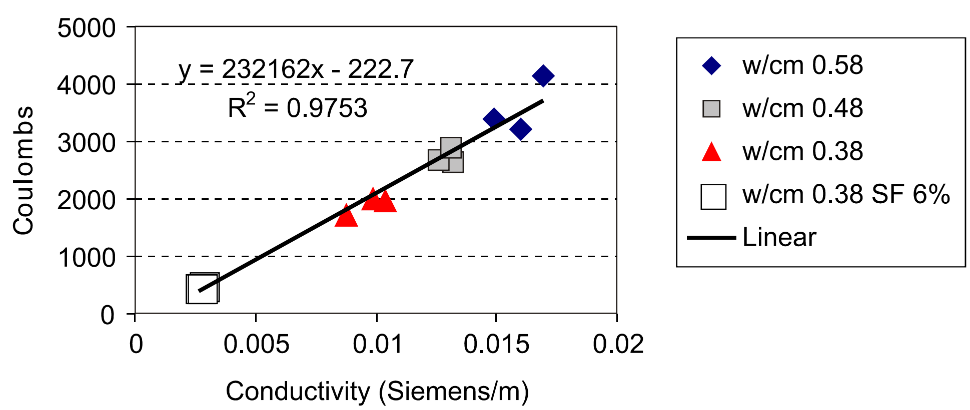

Figure 1. One-Minute Conductivity Values Plotted Against RCPT Values for Four Concretes

Data Analysis to Refine Relationship Between RCPT and Conductivity Test Results

In light of the good relationship between the conductivity and RCPT results, a large block of data collected during the RCPTs for a wide variety of concretes was analyzed to define the relationship more completely. In these data, initial and 10-min current values and the 6-hour total charge passed were available. Because the initial reading might fluctuate as the system stabilizes, the 10-min conductivity was used for comparison with the RCPT. Based on the data presented in Table 2, 1-min, 5-min, and 10-min conductivity values should relate similarly to the RCPT results. Figure 2 is a plot of the 10-min conductivity and RCPT values.

The relationship of the data shown in Figure 2 is described by a curvilinear regression. Upper and lower 95% confidence limits for the regression are shown. The confidence limits can be used to predict the range of RCPT values that would likely result from a test on concrete with a given conductivity value. The upper limit provides the maximum expected RCPT value for a given conductivity. As stated previously, VDOT's specifications for concrete permeability establish three classes with maximum RCPT values of 1500, 2500 and 3500 coulombs, respectively. Conductivity values corresponding to the intersection of the upper confidence limit with these given RCPT values are presented in Table 3 and can be used to determine whether the RCPT result for a concrete specimen is likely to exceed the specified maximum value. Concretes with conductivities below the given value can be considered to have passed the permeability requirement; those exceeding the value can be subjected to a full 6-hour RCPT until such time as the specification can be converted to a conductivity requirement.

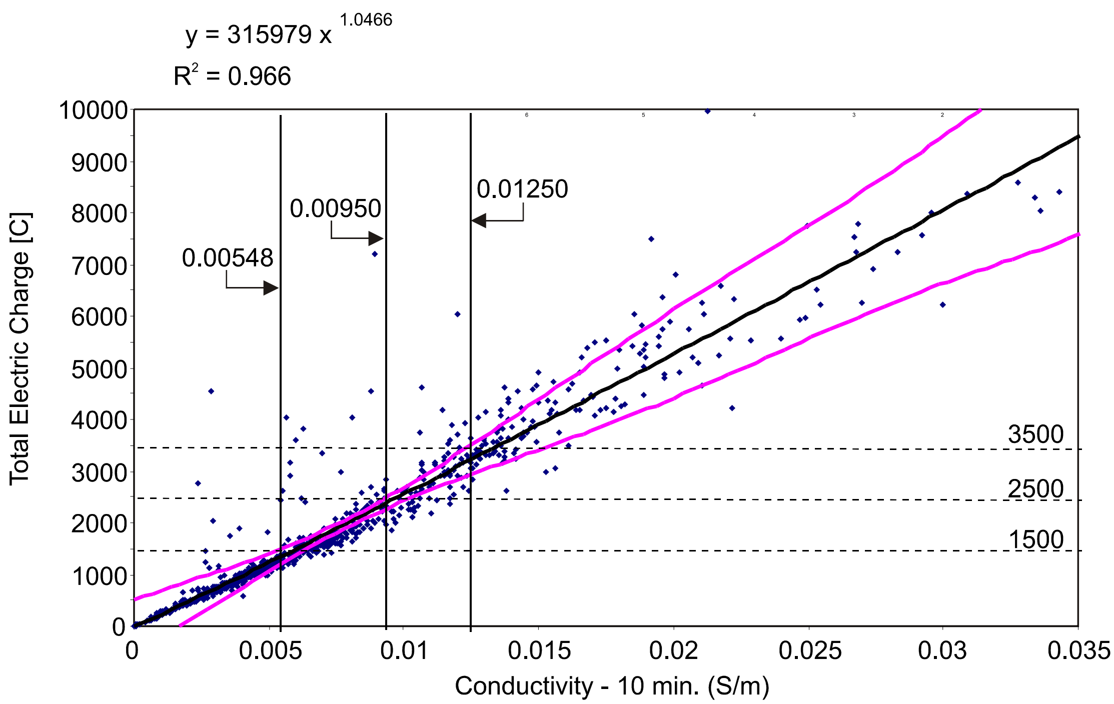

Figure 2. Relationship Between 10-min Conductivity and RCPT Values for Diverse Set of Concretes (n > 800). Regression and 95% confidence limits are plotted. Vertical lines mark the intercept of upper confidence limit with RCPT values of 1500, 2500, and 3500 coulombs. Corresponding conductivity values are 0.0055, 0.0095, and 0.125 S/m, respectively.

Table 3. Current VDOT-Specified Maximum RCPT Values and Corresponding Conductivity Values

Specified Maximum RCPT Value (coulombs)	Equivalent Maximum Conductivity (S/m)
1500	0.0055
2500	0.0095
3500	0.0125

CONCLUSIONS

- The electrical properties of concrete correspond well with the durability of the concrete as an indirect measure of the capillary pore system (affecting transport properties) and are a direct measure of the concrete's electrical conductivity (affecting the rate of steel corrosion).

- The commonly used RCPT introduces confounding influences during the 6-hour test period, producing a result that is less useful in evaluating the concrete than that of a simple and much more rapid measurement of the concrete's conductivity. The concrete conductivity can be determined using the RCPT equipment from a current reading at any time between 1 and 10 min after the 60-V potential is applied across the specimen.

- The test setup can be simplified by using the same electrolyte solution on both sides of the specimen. NaOH is preferred as the electrolyte as it is less corrosive to the electrode than is NaCl.

- The preparation of specimens for the conductivity test can be simplified as compared to that for the RCPT since the epoxy coating required for the latter is not needed because of the short duration of the test. If the test might be continued to determine the full 6-hour RCPT result, the sides of the specimen can be sealed with tape (e.g., electrician's tape) to prevent drying. Specimens should be saturated prior to conductivity testing, as the degree of saturation will affect the results.

- Conductivity values determined from current readings taken 1, 5, and 10 min after the voltage is applied are essentially the same and can be used to predict RCPT values. The repeatability (within-laboratory precision) of the conductivity measurement is estimated to be better than that of the RCPT test.

RECOMMENDATIONS

1. *Acceptance testing for conformance to concrete permeability specifications based on the RCPT should be streamlined by screening for potentially passing/failing concretes using the conductivity values listed in Table 3.* Concretes with conductivities not exceeding the applicable value can be considered acceptable. Concretes with values exceeding the limit can be subjected to the RCPT to determine compliance.

2. *Specifications based on the conductivity test should be written to replace those based on the RCPT using the conductivity values corresponding to current RCPT limits.* Further research may be desirable to establish more firmly appropriate conductivity limits for various concrete applications.

COST AND BENEFIT ANALYSIS

The benefits of implementing the recommendations provided are as follows:

- Routine acceptance testing of concrete for chloride permeability would be streamlined without increased cost.

- Such acceptance testing could be conducted within 1 to 10 minutes, as compared to 6 hours for the existing test procedure, thus greatly reducing the backlog associated with such testing. This would permit the timely reporting of test results to project personnel and allow more effective management.

- The new test recommended has improved repeatability when compared with the current test.

ACKNOWLEDGMENTS

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